91602
new 82-10

ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

To: Mr. D.A. Lee
Manager, Safety Services Department
Health & Safety Division, H2A20

MAGNETIC-FIELD EXPOSURE APPARATUS FOR SMALL-ANIMAL STUDIES: PHASE II

S.M. Harvey

Design criteria for a magnetic-field exposure apparatus intended for use in small-animal studies have been re-evaluated according to proposed changes in the study protocol. New designs based on minimizing the space and energy requirements are described.

INTRODUCTION

In a previous report/1/, design criteria were developed for a magnetic-field exposure facility suitable for use in a proposed study of EMF bioeffects in small animals. Following the issue of that report, significant changes were made in the scope and experimental protocol of the proposed study and a reanalysis of the design criteria was therefore undertaken. This showed that substantial changes in the design of the exposure apparatus would be required.

The revised study protocol and design criteria for a modified magnetic-field exposure apparatus are described in this report.

REVISED PROTOCOL

The following revisions to the original experimental protocol were provided to the Research Division:

- Consideration should be given to increasing the size of the exposed and sham-exposed groups (up to 100 animals each).

- Two sawtooth-type magnetic field waveforms should be used; the first to be at a frequency of 17 to 20 kHz with a sweep-time to flyback-time ratio of 9:1 and an amplitude of up to 200 μT peak-to-peak, the second to be at a frequency of 60 kHz with the same time ratio (9:1) and an amplitude up to 70 μT peak-to-peak. For both waveforms, the maximum dB/dt should be in the range from 30 to 50 T/s.

job	file	date	report no.
16-224	817.22	May 12, 1987	87-118-K

The implications of these changes in terms of apparatus design are: (a) up to twice the working volume within the field coils will be required, (b) the upper frequency-response limit of the coil driver will need to be three times higher, and (c) the peak-power requirements of the coil driver will need to be increased by up to 800 times.

REVIEW OF ORIGINAL DESIGN

The original exposure apparatus design described in reference 1 consists of a large (1.2 m) square helmholtz-type coil driven, for sawtooth-type fields, by a standard pulse generator through a professional-quality wide-band stereo amplifier.

The square coil, shown in Figure 1, is designed to provide a uniform (±5%) magnetic field over the volume occupied by up to 54 mice in their conventional cages. It is also designed as an open free-standing structure that does not transmit heat or vibration to the animal cages and does not restrict access, ventilation, movement, or other features of the normal animal environment.

The driver selected for this coil is a Yamaha model PC5002M amplifier rated at 1500 W into 8 ohms (both channels bridged) with a bandwidth of 100 kHz. The low output impedance of this type of commercially available amplifier allows the coil to be driven at high current with a simple low-voltage square-pulse waveform, as shown in Figure 2. In a series of tests, it was found that for a 20 kHz waveform with a time ratio of 9:1, the peak-to-peak current available from this amplifier depended on the inductance L of the coil (in μH) according to the following formula:

$$I_{p-p} = \frac{1035}{12.5+L} \text{ A.}$$

Available peak-to-peak fields can therefore be calculated for any coil if the field factor (ratio of field to current) and inductance of the coil are known. With the 1.2 m square coils described above, peak-to-peak fields of up to 50 μT are obtainable. However, at this level the output transistors overheat within a few minutes and special cooling modifications would be required for continuous operation. A 60 kHz waveform with a time ratio of 9:1 is not obtainable with the Yamaha amplifier.

Minimal perturbation of the normal laboratory environment and use where possible of off-the-shelf equipment were important considerations in the original design. The above considerations show that simply scaling up this design to meet the new study requirements is not very practical. In consequence, new design criteria based on minimizing space and energy requirements were evaluated.

NEW COIL DESIGNS

Coils that are smaller and more energy efficient than the original design can be used if the animal cages are redesigned to accommodate the required number of animals in approximately a cubical volume and if the coils are allowed to have three or more windings/2/3/. The drawbacks of these changes are that special cages have to be made and that access to the cages will be restricted. Two new coil designs are considered; one based on a sample size of 50 animals, and the other on a sample size of 100 animals.

Acceptable cage sizes for laboratory mice provide 100 cm^2 of area per mouse and a "rearing height" of 15 cm. Suitable custom cage designs for 50 and 100 mice satisfying these dimensions and allowing space for ventilation are shown in Figure 3. The new coil designs are based on these cage dimensions.

Preliminary design analysis showed that coils having three windings provide a substantial improvement over two-winding coils. More windings, up to and including a continuous current sheet, would of course provide further improvements but the benefits diminish fairly rapidly and may not justify the extra constraints. Three-winding coils having square windings with dimension D, variable spacing S between the outer windings, and outer/center turns ratios of 2/1 or 3/2 are used in the present analysis.

Results of some field calculations for various coil parameters are shown in Figure 4. These graphs show the locus of constant field uniformity, ±5% and ±10%, over the 50 and 100 mouse sample volumes for a coil with a turns ratio of 2/1 as the dimensions D and S are varied. The optimum coil dimensions are quite close to the apex of each curve and the corresponding coil designs are shown in Figures 5 and 6.

For the cubical 100 mouse sample volume, a turns ratio of 3/2 gives a slightly smaller and more energy efficient coil. Fringing fields for this coil are shown in Figure 7.

It may be noted that for the same field strength and number of animals, the new coil design will occupy about one half the space and require 3 to 4 times less peak power than the original design.

THE FRINGING FIELD PROBLEM

As shown in Figure 7, fringing fields can extend for a considerable distance around the coils. These fields must be maintained at an acceptable level in the vicinity of sham-exposed animals and must also be considered as a possible source of electromagnetic interference for electronic equipment in the vicinity.

Fringing fields may be reduced by shielding. To be effective, the shielding must consist of a continuous metallic loop surface (eg sheet or mesh) surrounding the coil and not too close to it. Unfortunately, such a shield represents a significant perturbation of the normal laboratory environment that may have to be taken into account in the experimental analysis.

Alternatively, fringing fields may be reduced by using more sophisticated coil designs, such as the "quadrupole" coil shown in Figure 8. Design optimization for these more complex coils is rather difficult in comparison with the customary "dipole" coils and to the author's knowledge has not previously been carried out for experiments of this kind. Dipole and quadrupole coils for 50-mouse capacity are compared in Appendix 1.

NEW DRIVER DESIGNS

The coil driver supplies the energy that is stored in the magnetic field during each half cycle. Other factors being equal, this energy is proportional to the sample volume (or number of animals N) and the square of the field strength B, ie:

$$E \propto NB^2$$

Extrapolation from the original apparatus design indicates that a pulse amplifier rated up to 20 kW with a bandwidth of 300 kHz will be required for the revised study protocol. Based on one telephone estimate, the price of an amplifier meeting these specifications is roughly CAN$80,000.

In this price range, the cost of developing alternative design approaches may be more than offset by savings on equipment costs. One such alternative approach is suggested by the typical flyback circuit used in most TV sets, which takes advantage of the fact that most of the energy stored in the magnetic field can be recovered and re-used. A conceptual low-cost coil driver design based on this circuit is shown in Figure 9.

The essential features of the conceptual design are:

- A low-voltage power supply that provides enough power to make up the losses in the driver circuit and coil.
- A large energy storage capacitor capable of supplying the instantaneous current requirements of the coil.
- A fast-acting switch capable of disconnecting the coil from the capacitor at full current.
- A high-voltage capacitor to generate the flyback voltage when the coil is disconnected.

With appropriate choice of design parameters, this circuit will produce the sawtooth field waveform shown in Figure 10. A linear flyback portion of the waveform may be obtained by replacing the flyback capacitor with a second energy-storage capacitor and switch, or by alternative methods of maintaining a constant V_+.

As a design exercise, some driver component specifications were estimated for an exposure apparatus designed for 50 mice with a field uniformity of ±10%. These are shown in Table 1. The specifications for the energy storage capacitor can probably be met by the present generation of fast-pulse forming capacitors although a special order may be necessary. Similarly, the switch specifications appear to be compatible with available power MOSFETs although some circuit development will be required.

Table 1

Coil driver component specifications based on a sample size of 50 animals and a field uniformity of ±10%.

Power Supply:	Voltage	25 V
	Current	1 A
Energy Storage Capacitor:	Voltage	25 V
	Capacitance	1000 μf
	Series inductance	<0.5 μh
Switch:	Peak "off" voltage	300 V
	Peak current	25 A
	"on" resistance	0.1 Ω
	switching time	0.5 μs

CONCLUSIONS

Because of changes in the experimental protocol of a proposed small-animal bioeffects experiment, a review of the original design criteria for a magnetic-field exposure facility has been carried out. This review shows that a simple scaling up of the original design is not practical. New design criteria based on minimizing space and energy requirements are therefore evaluated.

Replacing the original square Helmholtz-type coil with a new three-winding coil results in both space and energy savings. However, custom-built animal cages are required and access to the animals is restricted. Because of higher exposure fields, fringing fields from the coil are still a problem.

Pulse amplifiers capable of driving the new coils are quite expensive and alternative approaches are suggested that will take advantage of the possible recovery of energy from the magnetic field. A driver circuit based on TV flyback circuit technology is proposed and appears to be feasible with presently available components. However, further design and development work will be required.

Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

S.M. Harvey
Engineer/Physicist
Science Section

SMH:SMH:CB

REFERENCES

1. Design Criteria for a Small Animal Magnetic-Field Exposure Facility. Research Report 86-220-K.

2. Design Data for a Triple Coil System. Rev. Sci. Instrum. Vol 52, No 7, July, 1981. pp 1097-1099.

3. Uniform Magnetic Field Produced by Three, Four, and Five Square Coils. Rev. Sci. Instrum. Vol 54, No 7, July, 1983. pp 879-882.

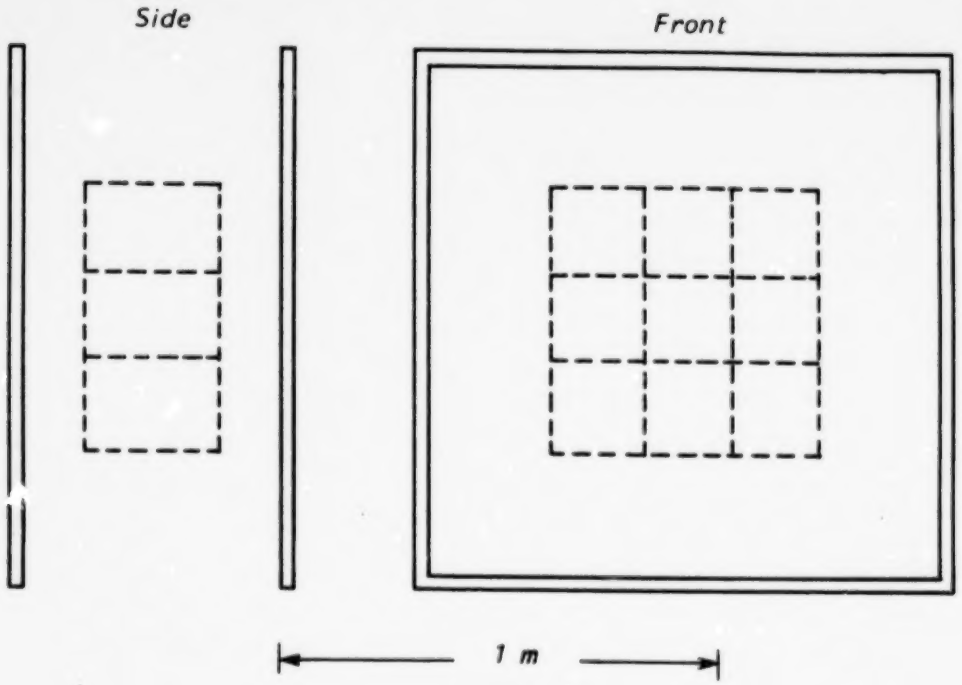


FIGURE 1

ORIGINAL SQUARE HELMHOLTZ-TYPE COILS.
DASHED LINES SHOW LOCATION OF STANDARD ANIMAL CAGES

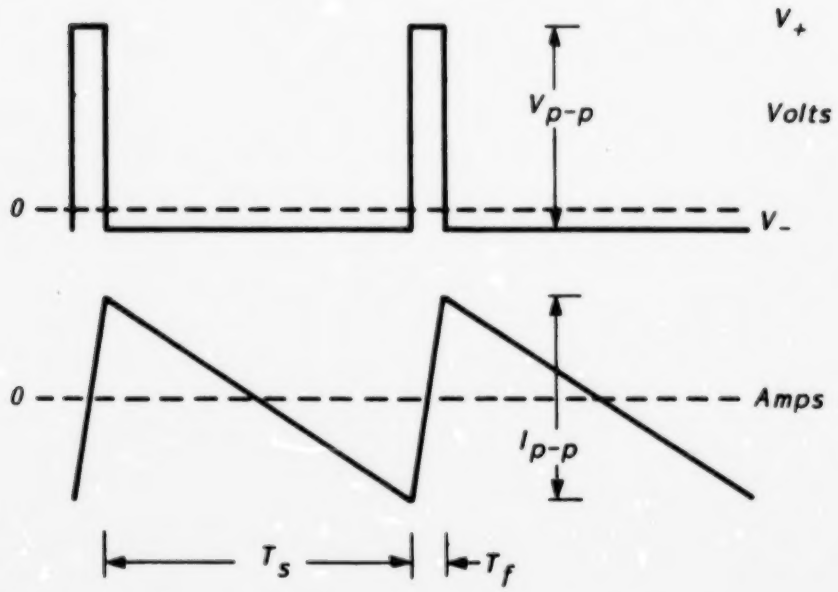
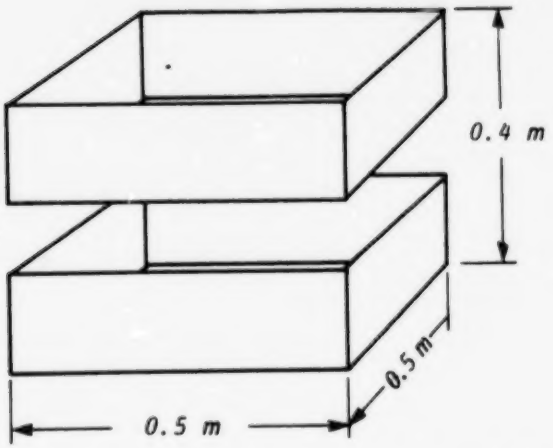


FIGURE 2

COIL VOLTAGE AND COIL CURRENT WAVEFORMS.
NOMINALLY, $V_- = L\ I_{p-p}/T_s$ AND $V_+ = L\ I_{p-p}/T_f$ WHERE T_s IS SWEEPTIME, T_f IS FLYBACK TIME, AND L IS COIL INDUCTANCE

50 Mice



100 Mice

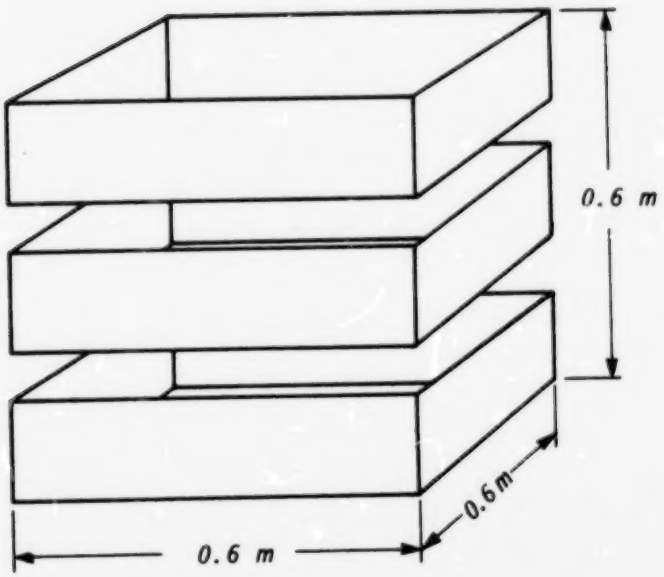


FIGURE 3
CUSTOM CAGE DESIGNS

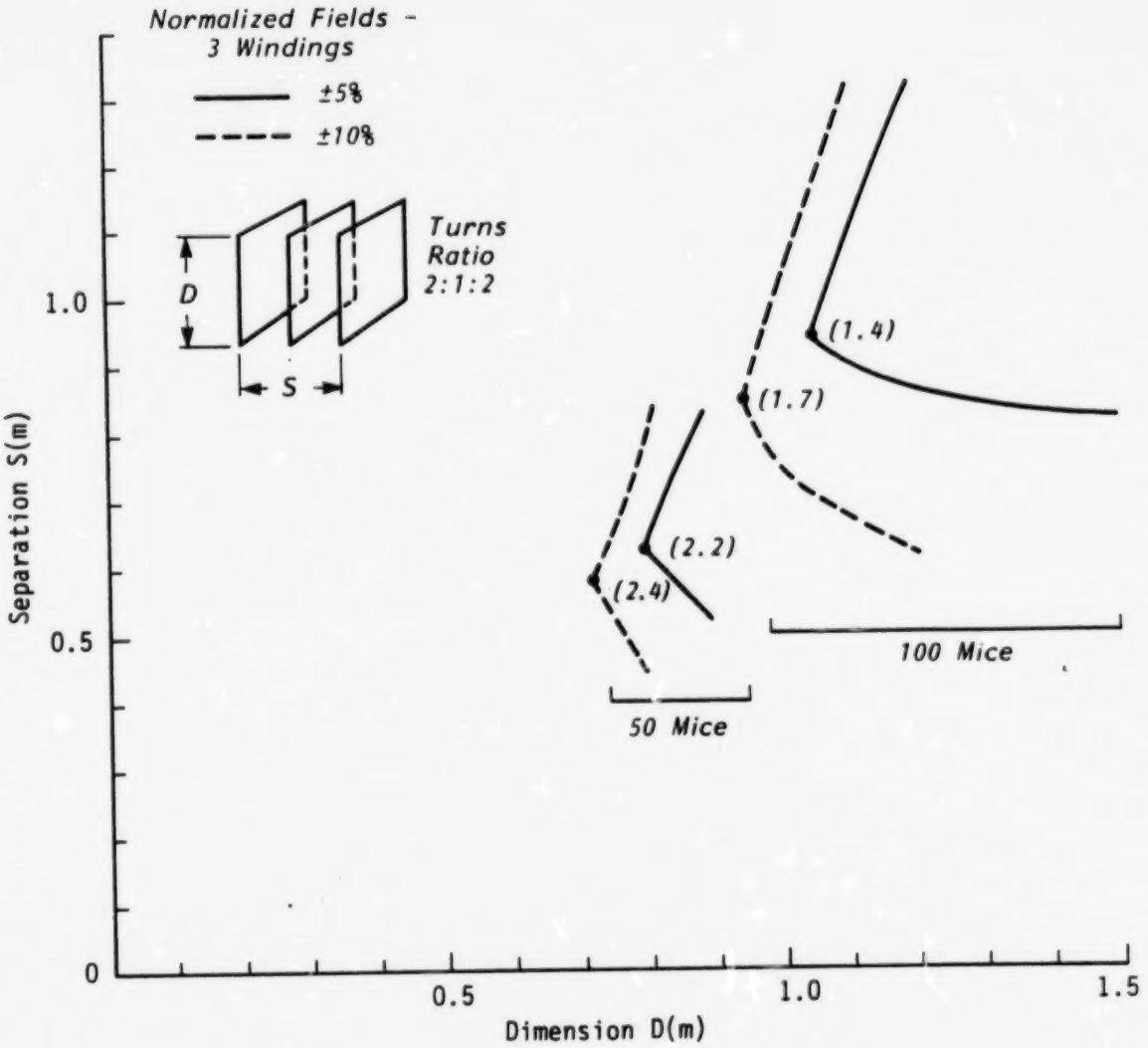


FIGURE 4

PLOTS OF CONSTANT FIELD UNIFORMITY OVER ANIMAL CAGES. THREE-WINDING COILS. RELATIVE FIELD STRENGTHS AT OPTIMUM ARE SHOWN IN BRACKETS

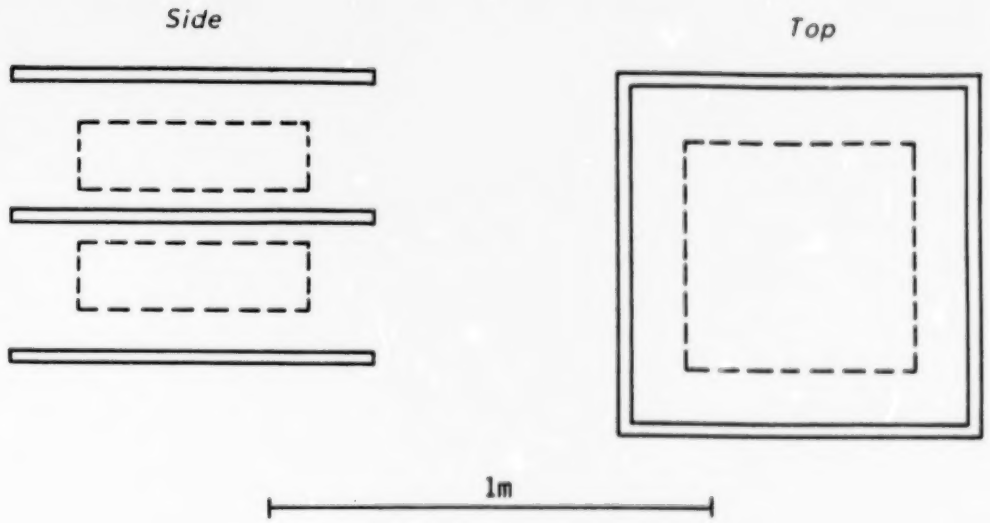


FIGURE 5
3-WINDING COIL FOR 50 MICE

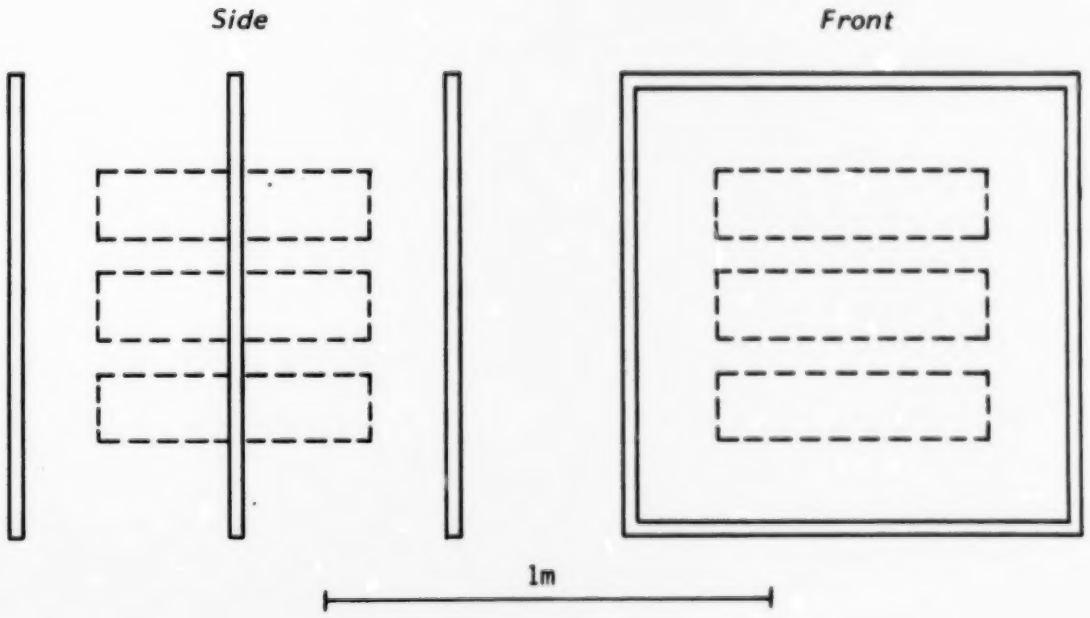


FIGURE 6
3-WINDING COIL FOR 100 MICE

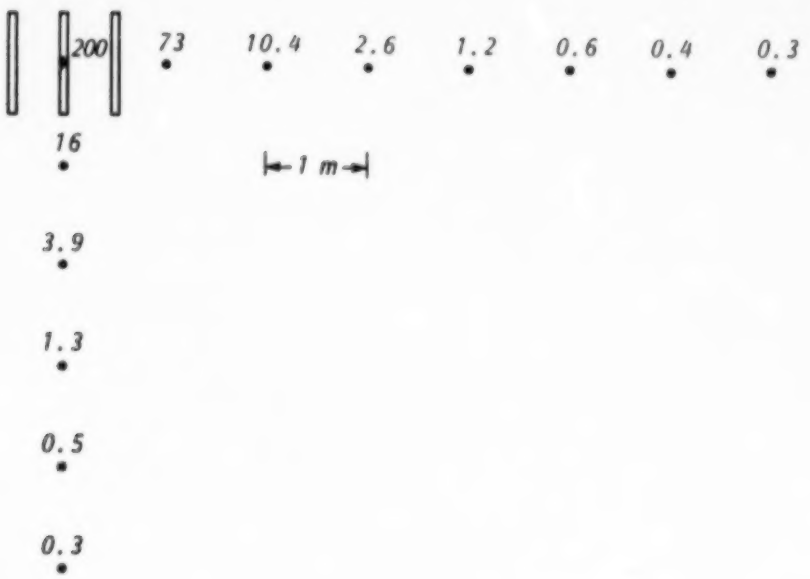
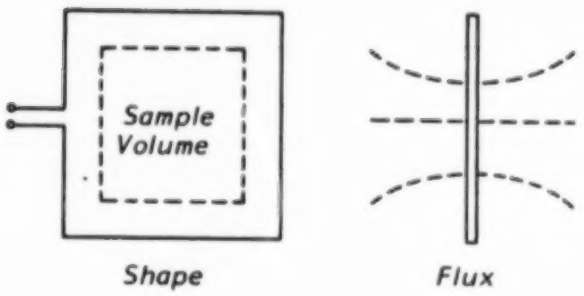
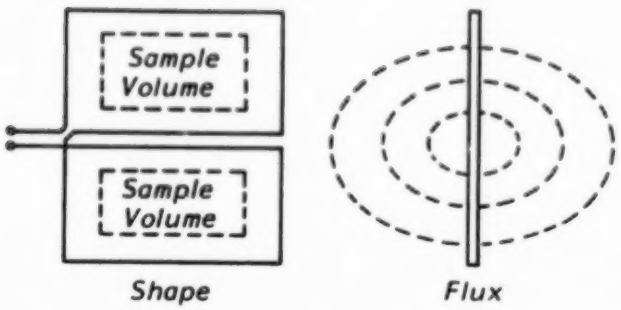


FIGURE 7
3-WINDING COILS FOR 100 MICE
VALUES OF B_{p-p} (μT) VS DISTANCE



Dipole Coil



Quadrupole Coil

FIGURE 8
COIL-WINDING TOPOLOGIES

174801-RD

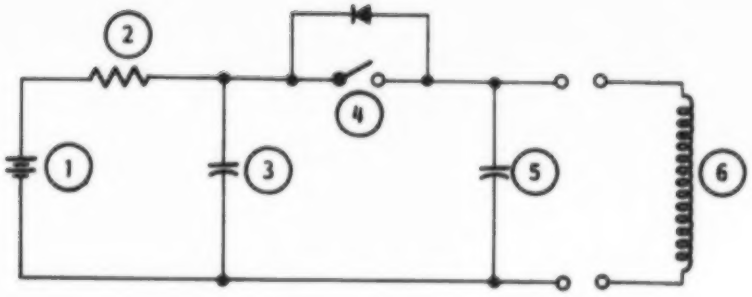


FIGURE 9
SCHEMATIC OF CONCEPTUAL
ENERGY-EFFICIENT COIL DRIVER

(1) LOW-VOLTAGE POWER SUPPLY
(2) CURRENT LIMITING RESISTOR
(3) ENERGY-STORAGE CAPACITOR
(4) FAST-ACTING SWITCH
(5) FLYBACK CAPACITOR
(6) COIL

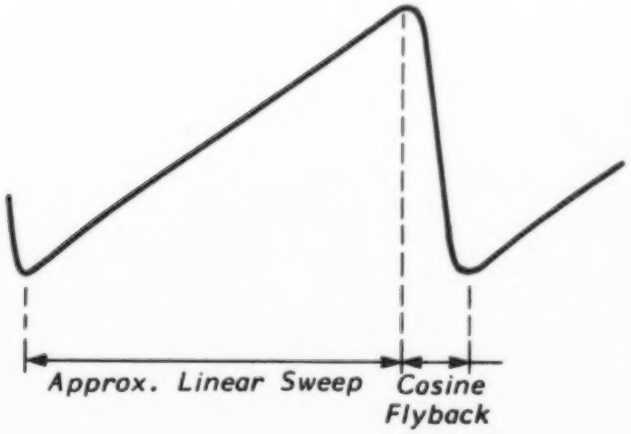


FIGURE 10
WAVEFORM PRODUCED BY
COIL-DRIVER OF FIGURE 9

174802-RD

APPENDIX I

QUADRUPOLE COIL DESIGN

The potential benefits of the quadrupole coil-winding configuration for reducing troublesome fringing fields are evaluated in this appendix.

For comparison purposes, a 50-mouse exposure apparatus providing a field uniformity of +/- 10% over the cage volume is assumed. It is also assumed that the mice will be accomodated in two tiers each providing space for 25 mice (2500 cm^2) with a rearing height of 15 cm.

Three different coils are evaluated: a 3-winding dipole coil, a 3-winding quadrupole coil, and a 4-winding quadrupole coil. For each coil, the field magnitudes are calculated on a 3 to 4 cm grid over the appropriate sample volume. The coil dimensions, winding ratios, and position of the cages within the coil are then varied to achieve the minimum coil size consistent with the stated constraints. For the purpose of these calculations, the coil windings are assumed to have negligible current-carrying cross section.

The resulting coils are shown in Figure A1. This Figure shows that simply changing from a dipole to a quadrupole winding in a 3-winding coil results in a 20% increase in coil volume, extra space being required between the two cage tiers for the central conductors. By adding a fourth winding to the quadrupole coil, the dimensions of the original dipole coil are restored and, in fact, slightly reduced. Turns ratios and field factors for the three coils are given in Table A1.

Fringing fields for the three coils are shown in Figure A2. This figure illustrates the substantially increased rate of fall-off (an R^{-4} rather than an R^{-3} dependence) of the fringing fields produced by the quadrupole winding configuration, which should eliminate potential interference problems with equipment in adjacent rooms. If a fringing field of 0.1 μT peak-to-peak is taken as a criterion for the location of other exposure groups, then the point of closest approach is reduced from about 5 m, measured from the center of the dipole coil, to about 2 m, measured from the center of the 4-winding quadrupole coil.

Table A1

Coil	Turns Ratio	Field Factor*
Dipole - 3-Winding	3:2:3	7.7
Quadrupole - 3-Winding	3:2:3	9.3
Quadrupole - 4-Winding	2:1:1:2	8.6

* Field factor is the field (in μT) produced at the animal cages for 1 amp of supplied current. Coil efficiency depends not only on the field factor but also on the coil inductance.

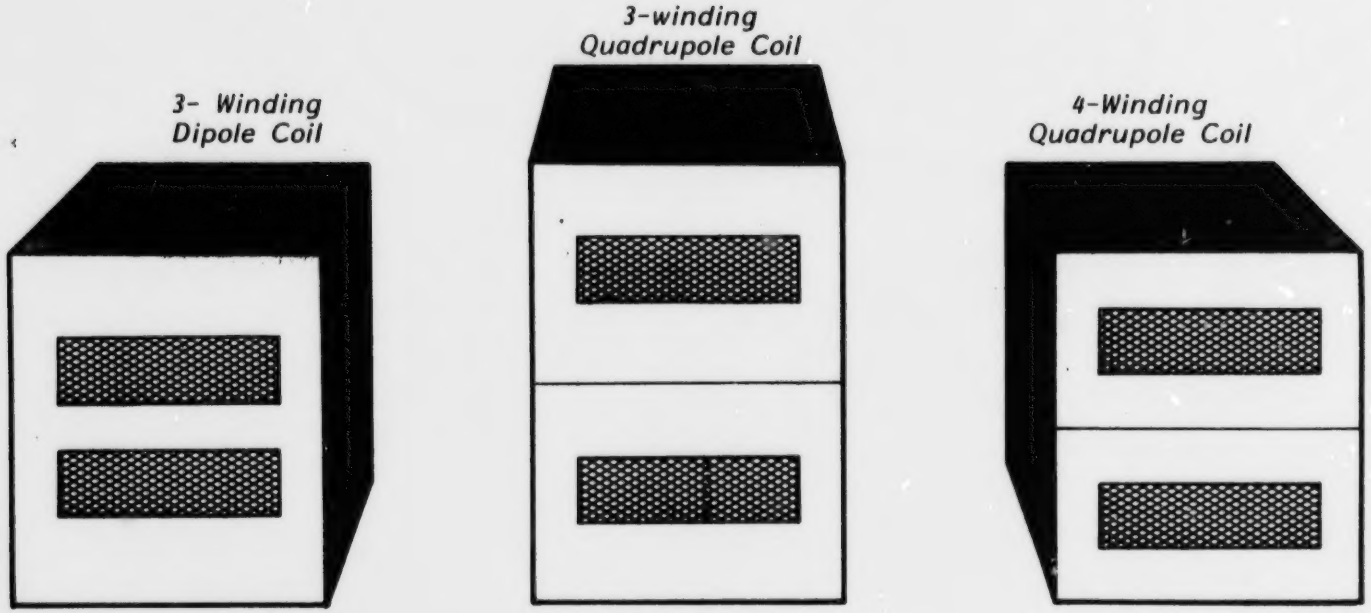


FIGURE A1
COIL DIMENSIONS

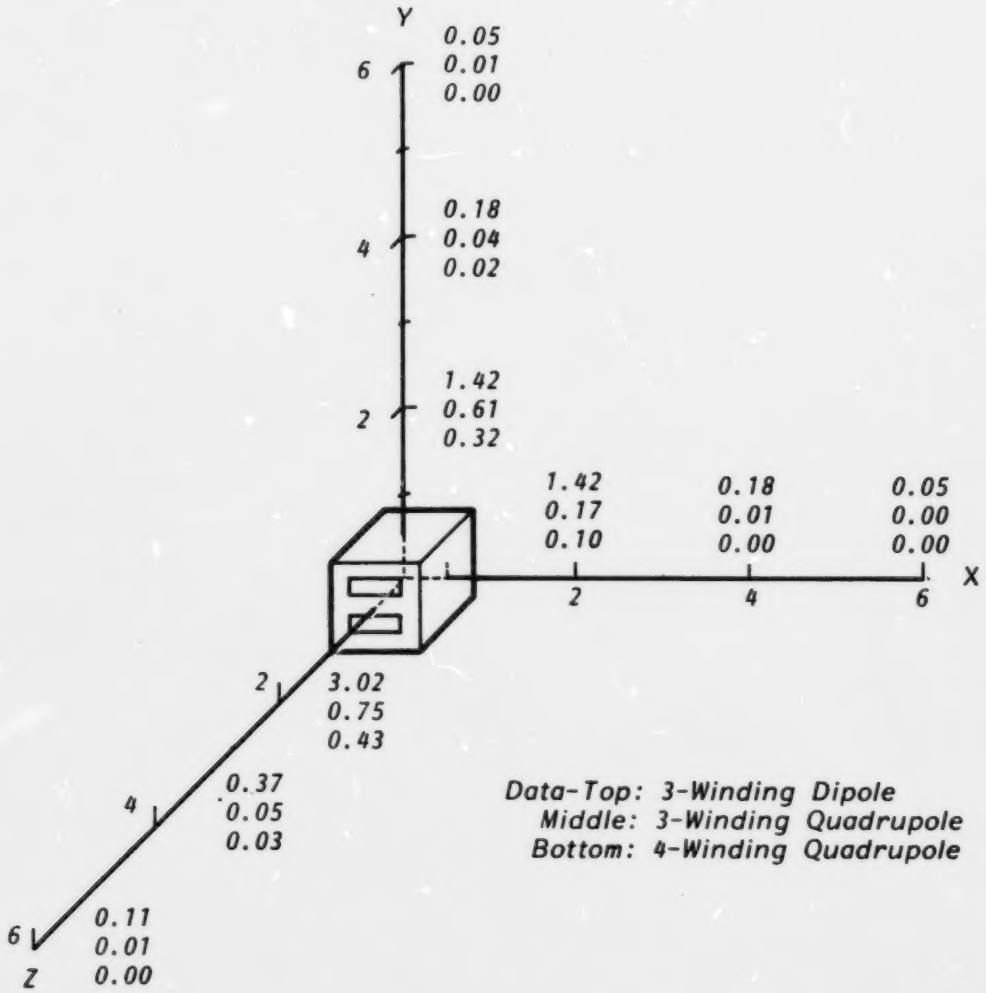


FIGURE A2

FRINGING FIELDS AS A FUNCTION OF DISTANCE (IN METERS) ALONG X,Y,Z AXES CENTER FIELD IS 200 μT

174898-RD

DISTRIBUTION

Mr. D.A. Lee	Health and Safety, H2A20
Mr. R. Wilson	Health and Safety, H2 A27
Mr. M.L. Walsh	Health and Safety, Pickering
Mr. D. Agnew	Health and Safety, Pickering
Dr. G.L. Vascotto	Research Division
Mr. A.F. Baljet	Research Division
Mr. R.D. Brown	Research Division
Dr. N. Anyas-Weiss	Research Division
Dr. K.E. Donnelly	Research Division
Dr. S.M. Harvey (3)	Research Division

Public Reference Centre
Editorial Section (2)
Office Copies (2)
Extra Copies (3)